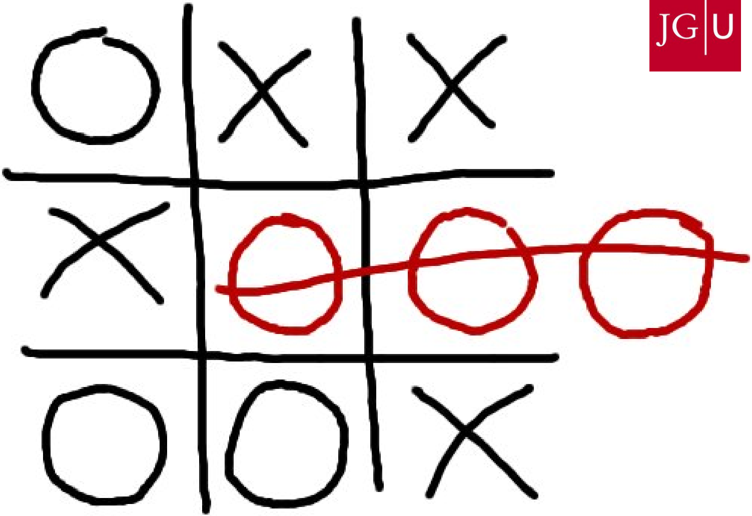


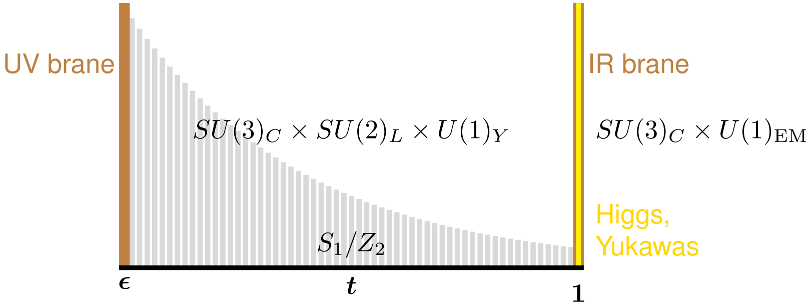
Solving the RS Flavor Problem and the $t\bar{t}$ Forward Backward Asymmetry

Martin Bauer, Mainz

with Raoul Malm
and Matthias Neubert

1. Flavor in RS Models
2. The RS Flavor Problem
3. Solving the RS Flavor Problem
4. Solving the $t\bar{t}$ Forward Backward Asymmetry
5. Dijet Bounds

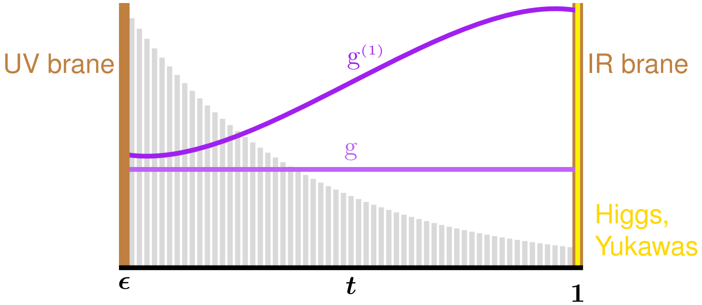
Flavor in RS Models



$$ds^2 = \frac{\epsilon^2}{t^2}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - \frac{1}{k^2t^2}dt^2$$

$$\epsilon = \frac{\Lambda_{\mathrm{Weak}}}{\Lambda_{\mathrm{PL}}} \qquad L = -\log\epsilon \approx 37$$

Flavor in RS Models



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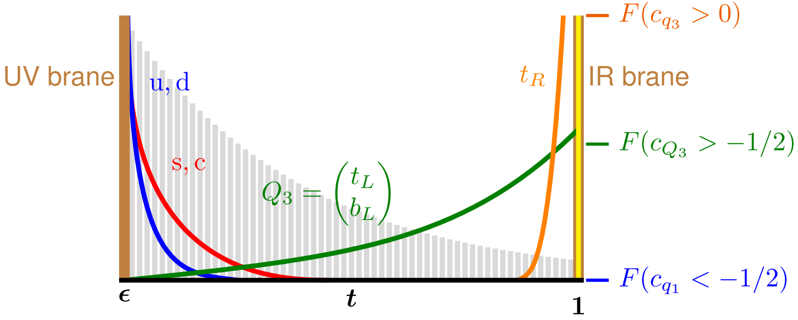
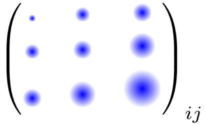


Flavor in RS Models

- Yukawa matrices $(Y_d)_{ij}$ can be chosen to be anarchic and of order one:

$$(Y_d^{\text{eff}})_{ij} \equiv F(c_{Q_i})(Y_d)_{ij}^{(5D)} F(c_{d_j}) \sim$$



- Hierarchical masses and mixings can be generated by relying on order one parameters only:

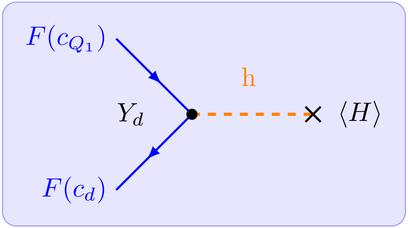
$$m_{q_i} = \mathcal{O}(1) \frac{v}{\sqrt{2}} F(c_{Q_i}) F(c_{q_i})$$

$$\bar{\rho}, \bar{\eta} = \mathcal{O}(1)\,, \qquad \lambda = \mathcal{O}(1) \frac{F(c_{Q_1})}{F(c_{Q_2})}\,, \qquad A = \mathcal{O}(1) \frac{F^3(c_{Q_2})}{F^2(c_{Q_1}) F(c_{Q_3})}$$

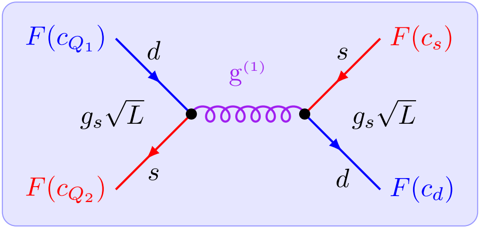
Flavor in RS Models

The parameters which control the masses of the light quarks suppress potentially dangerous FCNC's : RS-GIM.

$$
\begin{aligned}
m_d &\sim \frac{v}{\sqrt{2}}\, F(c_{Q_1})\, Y_d^{(5D)}\, F(c_d) \\
&\sim \frac{v}{\sqrt{2}}\, Y_d^{\text{eff}}
\end{aligned}
$$



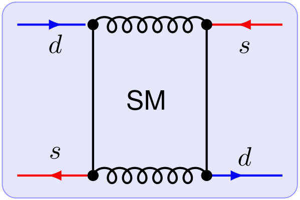
$$
\begin{aligned}
&\frac{g_s^2\, L}{M_{\text{KK}}^2}\, F(c_{Q_1}) F(c_d) F(c_{Q_2}) F(c_s) \\
&\sim \frac{g_s^2}{M_{\text{KK}}^2} L \frac{2 m_d m_s}{\left(v Y_d^{(5D)}\right)^2}
\end{aligned}
$$



The RS Flavor Problem

The RS-GIM mechanism is extremely effective, apart from one observable,

$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\mathrm{exp}}} \, \mathrm{Im}\, \langle K^0 | \mathcal{H}_{\mathrm{eff}}^{\Delta S=2} | \bar{K}^0 \rangle \,,$$



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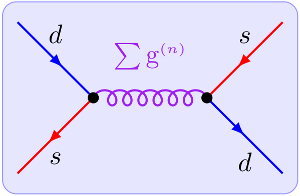

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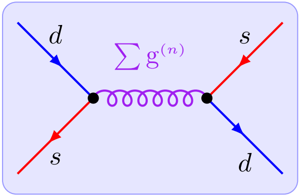
$$Q_1^{sd} = (\bar{d}_L\gamma^\mu s_L)\,(\bar{d}_L\gamma_\mu s_L)$$

$$\widetilde{Q}_1^{sd} = (\bar{d}_R\gamma^\mu s_R)\,(\bar{d}_R\gamma_\mu s_R)$$

$$\boxed{Q_4^{sd} = -\tfrac{1}{2}(\bar{d}_R^\alpha\gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta\gamma_\mu s_L^\alpha)}$$

$$Q_5^{sd} = -\tfrac{1}{2}(\bar{d}_R\gamma^\mu s_R)\,(\bar{d}_L\gamma_\mu s_L)$$



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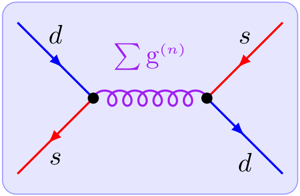

$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left(\boxed{C_4^{\rm RS}} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

Large chiral enhancement $\sim \left(\frac{m_K}{m_s + m_d} \right)^2$

RGE running
$3\,\text{TeV} \to 2\,\text{GeV}$

The RS Flavor Problem

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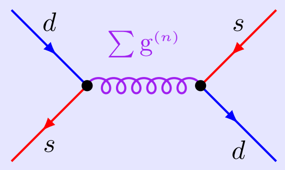

$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

$$\langle B | \mathcal{H}_{\rm RS}^{\Delta B=2} | \bar{B} \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 7 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

$$\langle D | \mathcal{H}_{\rm RS}^{\Delta C=2} | \bar{D} \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 13 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

Solving the RS Flavor Problem

If we had a gauge boson which couples with opposite sign to left- and right-handed quarks, but with the same coupling strength as the KK gluon tower, we could evade the ϵ_K- constraint. Something like a 5D axigluon.

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Extend the strong bulk gauge group to $SU(3)_{\text{Doublet}} \otimes SU(3)_{\text{Singlet}}$

$$\mathcal{L}_{\text{int}} \ni g_D \, \bar{Q} \, G^D_\mu \gamma^\mu Q + g_S \, \bar{q} \, G^S_\mu \, \gamma^\mu q$$

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$$\mathcal{L}_{\mathrm{int}} \ni g_D \, \bar{Q} \, G^D_\mu \gamma^\mu Q + g_S \, \bar{q} \, G^S_\mu \, \gamma^\mu q$$

and break it via boundary conditions (we do not need a strong Higgs here) into the gluon

$$g_\mu = G^D_\mu \cos\theta + G^S_\mu \sin\theta \qquad \text{with} \qquad \tan\theta = g_D/g_s$$

and the *axigluon* (only for $\tan\theta = 1$ it is a clean axigluon)

$$A_\mu = G^D_\mu \sin\theta - G^S_\mu \cos\theta$$

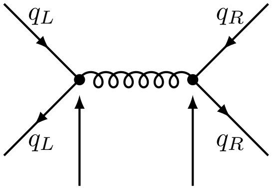
so that

$$\begin{aligned}\mathcal{L}_{\mathrm{int}} \ni \; & g_s \, (\bar{Q} \, g_\mu \gamma^\mu Q + \bar{q} \, g_\mu \, \gamma^\mu q \,) \\ & + g_s \, (\tan\theta \; \bar{Q} \, A_\mu \gamma^\mu Q - \cot\theta \; \bar{q} \, A_\mu \, \gamma^\mu q \,)\end{aligned}$$

Solving the RS Flavor Problem

Since the SM quarks are (up to small admixtures suppressed by the KK scale), the zero modes of the 5D doublets/singlets respectively, we achieve the opposite sign coupling, independent of the mixing angle θ

$C_4 \sim$



KK gluon: g_s g_s

KK *axigluon*: $g_s \tan\theta$ $-g_s \cot\theta$

Note that for $C_1/\widetilde{C}_1$ the contributions add up!

The contributions cancel, if the flavorchanging non-diagonal couplings are the same. These are specified by overlap integrals of the whole tower of KK bosons with the profile functions of the SM quarks.

$\Rightarrow$ Set by the boundary conditions.

Solving the RS Flavor Problem

We have to sum over the KK modes

$$D(t,t';p) = \sum_{n=0} \frac{\chi_n(t)\chi_n(t')}{p^2 - m_n^2 + i\epsilon} \approx \sum_{n=0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2},$$

with general BCs:

$$\chi_n(t)\big|_{t=\epsilon} = \frac{a_\epsilon}{2}\,\partial_t\chi_n(t)\big|_{t=\epsilon} \qquad \chi_n(t)\big|_{t=1} = \frac{a_1}{2}\,\partial_t\chi_n(t)\big|_{t=1}$$

The gluon needs Neumann BCs on both branes in order to have a massless zero mode $(a_1, a_\epsilon \to \infty)$

$$\sum_{n\geq 1} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{1}{4\pi M_{\mathrm{KK}}^2}\left[\; L\,t_<^2 - t^2\left(\tfrac{1}{2} - \ln t\right) - t'^2\left(\tfrac{1}{2} - \ln t'\right) + \tfrac{1}{2L}\right],$$

Solving the RS Flavor Problem

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where these terms are responsible for $\Delta F = 2$ effects

Solving the RS Flavor Problem

Choosing Neumann BCs on one brane leads to

$$\sum_{n\geq 0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2}\bigg|_{a_\epsilon\to\infty} = \frac{L}{4\pi M_{\mathrm{KK}}^2}\left(t_<^2 - t^2 - t'^2 + 1 - a_1\right),$$

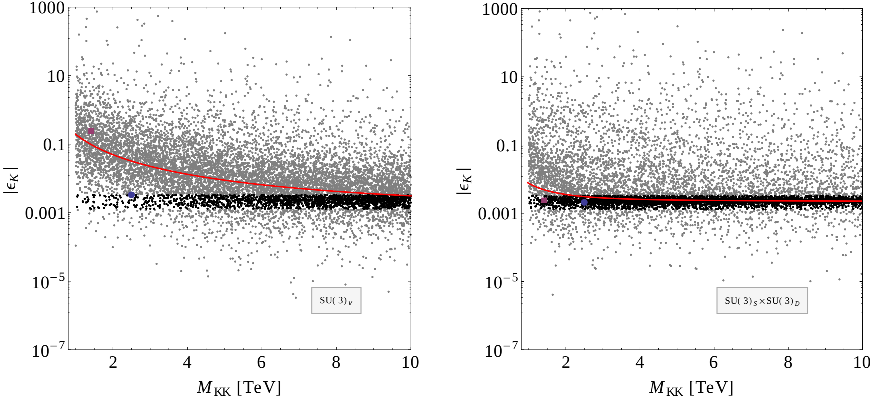
$$\sum_{n\geq 0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2}\bigg|_{a_1\to\infty} = \frac{L}{4\pi M_{\mathrm{KK}}^2}\left(t_<^2 + \epsilon\, a_\epsilon\right).$$

Both cases lead to identical $\Delta F = 2$ overlap integrals, i.e. couplings as in the NN case.

Therefore there is a cancellation of the contributions to the dangerous mixed chirality operators, while the equal chirality operators get a factor 2.

Therefore, effects in B and D mixing are still there.

Solving the RS Flavor Problem



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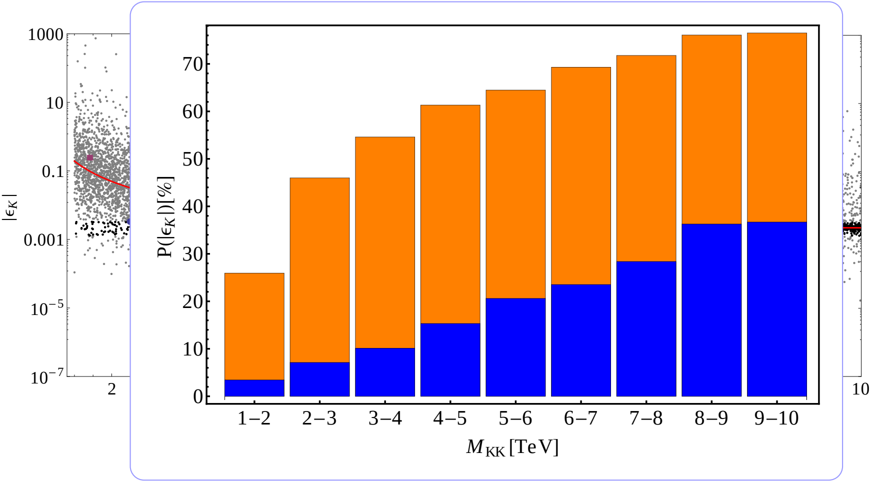

Solving the RS Flavor Problem

$$\sum_{n\geq 1} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{L}{4\pi M_{\rm KK}^2}\Big[\,t_<^2 - \frac{1}{L}t^2\left(\frac{1}{2} - \ln t\right) - \frac{1}{L}t'^2\left(\frac{1}{2} - \ln t'\right) + \frac{1}{2L^2}\Big]$$

$$\sum_{n\geq 0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{L}{4\pi M_{\rm KK}^2}\big(t_<^2 - t^2 - t'^2 + 1 - a_1\big) \qquad \longleftarrow \text{ Scenario 1}$$

$$\sum_{n\geq 0} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{L}{4\pi M_{\rm KK}^2}\big(t_<^2 + \epsilon\, a_\epsilon\big) \qquad \longleftarrow \text{ Scenario 2}$$

In Scenario 1 the *axigluon* couplings dominate the $\Delta F = 1$ sector.

Its coupling can have a large axial component ($\theta \sim 45^\circ$) and due to the sum over KK modes $\Delta F = 1$ contributions come with a negative sign.

That is exactly what is needed in order to explain the top pair forward backward asymmetry.

Solving the RS Flavor Problem

$$\sum_{n\geq 1} \frac{\chi_n(t)\,\chi_n(t')}{m_n^2} = \frac{L}{4\pi M_{\mathrm{KK}}^2}\left[t_<^2 - \frac{1}{L}t^2\left(\frac{1}{2} - \ln t\right) - \frac{1}{L}t'^2\left(\frac{1}{2} - \ln t'\right) + \frac{1}{2L^2}\right]$$

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Solving the $\mathrm{t\bar{t}}$ Forward Backward Asymmetry

For a large $t\bar{t}$ forward backward asymmetry we need the axial couplings to be large. The vector couplings must be small if we do not want to spoil the excellent agreement in the symmetric cross section.

$$\left(A^{t}_{\mathrm{F}B}\right)^{\mathrm{p\bar{p}}}_{\mathrm{exp}} = (15.0 \pm 5.0_{\mathrm{stat.}} \pm 2.4_{\mathrm{syst.}})\% \qquad \propto C_{A}$$

$$\left(A^{t}_{\mathrm{F}B}\right)^{\mathrm{p\bar{p}}}_{\mathrm{SM}} = (5.1 \pm 0.6)\,\%$$

$$\left(\sigma_{t\bar{t}}\right)_{\mathrm{exp}} = (7.50 \pm 0.31_{\mathrm{stat.}} \pm 0.34_{\mathrm{syst.}} \pm 0.15_{\mathrm{lumi.}})\,\mathrm{pb}$$

$$\left(\sigma_{t\bar{t}}\right)_{\mathrm{SM}} = \left(6.73^{\;0.52}_{-0.80}\right)\mathrm{pb} \qquad \propto C_{V}$$

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In terms of the effective Hamiltonian

$$\mathcal{H}_{\mathrm{eff}} = \sum_{q=u,d}\;\sum_{A,B=L,R} C^q_{AB}\,(\bar{q}\,\gamma_\mu T^a\,P_A\,q)(\bar{t}\,\gamma^\mu T^a\,P_B\,t)\,,$$

the axial and vector 4 fermion couplings are

$$C^q_{A/V} = \mathrm{Re}\left[\left(C^q_{LR} + C^q_{RL}\right) \mp \left(C^q_{LL} + C^q_{RR}\right)\right]$$

Solving the $t\bar{t}$ Forward Backward Asymmetry

This leads to

$$
\begin{aligned}
C_A^q =& \frac{2\pi\alpha_s}{M_{\rm KK}^2} L \Big[(2+\tan^2\theta+\cot^2\theta)(a_1-1) \\
& + (1+\tan^2\theta)(\Delta_Q)_{33} + (1+\cot^2\theta)(\Delta_u)_{33} \Big] \,, \\
C_V^q =& \frac{2\pi\alpha_s}{M_{\rm KK}^2} L \Big[(\tan^2\theta+\cot^2\theta-2)(a_1-1) \\
& - (1-\tan^2\theta)(\Delta_Q)_{33} - (1-\cot^2\theta)(\Delta_u)_{33} \\
& - \frac{2}{L}\Big(\frac{1}{L} - (\Delta'_Q)_{33} - (\Delta'_u)_{33} \Big) \Big] \qquad \longleftarrow \qquad \text{Gluon KK modes!}
\end{aligned}
$$

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\end{aligned}$$

Gluon KK modes!

No universal terms → $\boxed{a_1 = 1}$

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$$
\begin{aligned}
C_A^q =& \frac{2\pi\alpha_s}{M_{\rm KK}^2} L \Big[(2 + \tan^2\theta + \cot^2\theta)(a_1 - 1) \\
& + 2(\Delta_Q)_{33} + 2(\Delta_u)_{33} \Big] , \\
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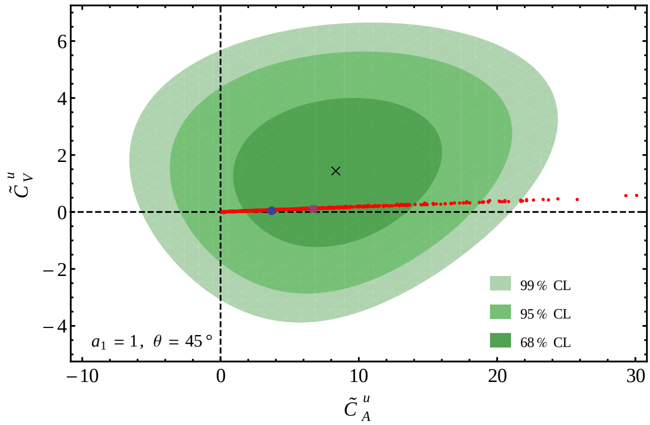
\end{aligned}
$$

Gluon KK modes!

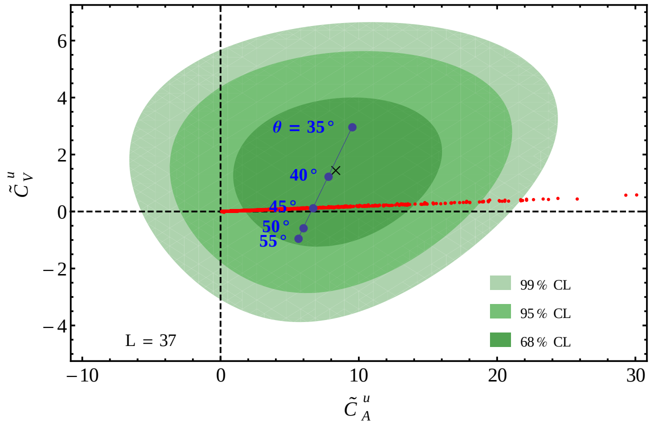
No universal terms $\rightarrow$ $\boxed{a_1 = 1}$

Small vector and large axial couplings $\rightarrow$ $\boxed{\theta = 45^\circ}$

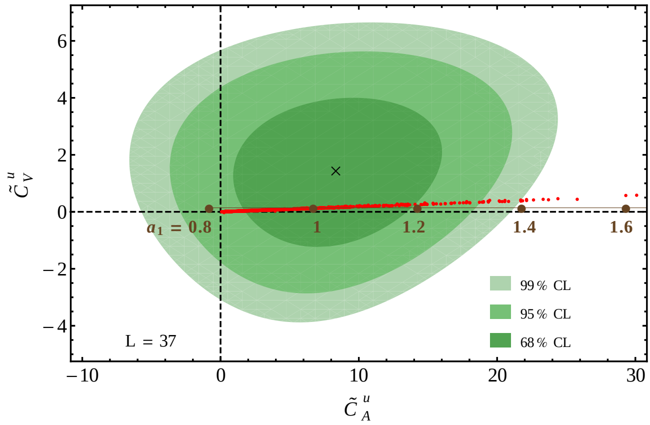
$$\boxed{\frac{C_V}{C_A} \sim \frac{1}{L}}$$



Sample parameter points at $M_{\rm KK} = 1.5\,\rm TeV$ and $M_{\rm KK} = 2.5\,\rm TeV$.



Varying the mixing angle $\theta \in [35, 55]$.



Varying boundary conditions $a_1 = 0.8 - 1.6$.

Dijet Bounds

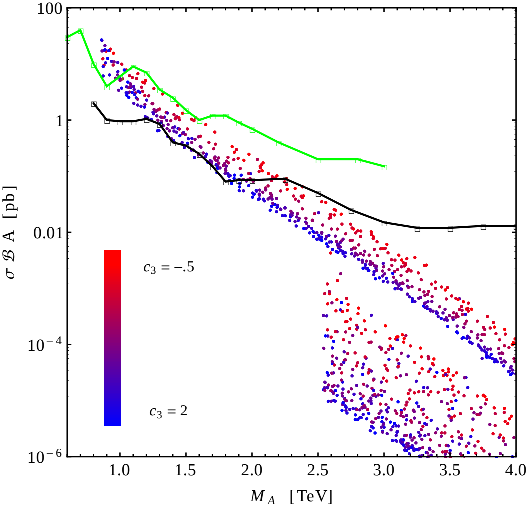
Another nice feature of this extension is, that the lightest strong coupling KK mode is not the KK gluon with

$$m_{g^1} = 2.5\, M_{\mathrm{KK}}$$

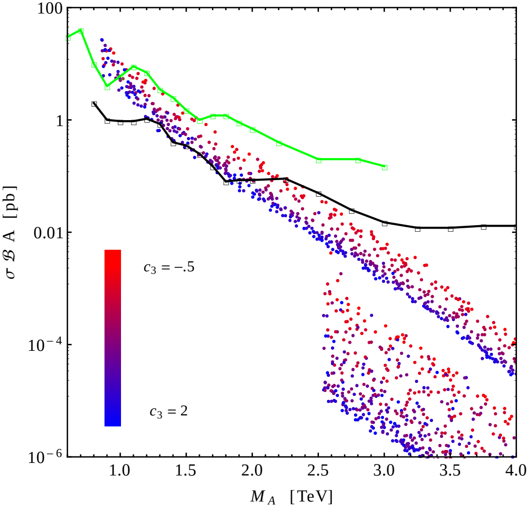
but the first *axigluon* mode with

$$\begin{aligned} m_{a^1} &= 0.86\, M_{\mathrm{KK}} \qquad & a_1 &= 1 \\ m_{a^1} &= 1.09\, M_{\mathrm{KK}} \qquad & a_1 &= 1.1 \\ m_{a^1} &= 1.28\, M_{\mathrm{KK}} \qquad & a_1 &= 1.2 \\ m_{a^1} &= 1.42\, M_{\mathrm{KK}} \qquad & a_1 &= 1.3 \\ &\vdots \end{aligned}$$

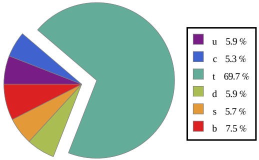
Dijet Bounds



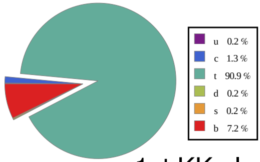
Dijet Bounds



Branching Ratios:



1st axigluon



1st KK gluon

Conclusions

- The axigluon solves the RS flavor problem: Allows for $M_{\mathrm{KK}} \sim 1$ TeV.
- The sum over KK modes provides the correct sign and through the RS flavor mechanism the correct magnitude couplings in order to explain the ttbar forward backward asymmetry.
- The corresponding first mode would be the lightest signal of the RS model.
- What about electroweak precision observables :
  - Custodial symmetry?
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